INSTITUTE OF GAS TECHNOLOGY

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A STUDY OF THE FUNDAMENTALS OF COMBUSTION

REPORT NO. 9

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CONTRACT NONR-04100

MARCH, 1954

OFFICE OF NAVAL RESEARCH

WASHINGTON, D. C.

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SUMMARY

This report presents the work performed during the period July 1, 1953, to December 31, 1953, on "A Study of the Fundamentals of Combustion," jointly sponsored by the Office of Naval Research, Science Division, Power Branch and by the Institute of Gas Technology in the laboratories of the Institute of Gas Technology at Chicago, Illinois.

The results of a study of the burning velocity of the methane-oxygen-nitrogen system at a theoretical adiabatic flame temperature of 2250°K at one atmosphere pressure are presented. Ten mixtures which yield theoretical adiabatic flame temperatures of 2250°K at one atmosphere pressure were calculated for each of the systems methane-oxygen-nitrogen, methane-oxygen-argon, and methane-oxygen-helium.

The burning velocities of the methane-oxygen-nitrogen system at 2250°K were substantially higher than the burning velocities for the 2000°K isotherm previously reported. For the system methane-oxygen-nitrogen at 2250°K a maximum burning velocity was observed in the 7.0:1.0 to 8.0:1.0 oxygen to methane mole ratio range, which is approximately the same as for the 2000°K isotherm.

EXPERIMENTAL PROCEDURE

The burning velocities were experimentally determined on a Toeppler-Schlieren type optical system. Combustion took place on a one-quarter inch water-jacketed burner tube. The burner inlet composition was determinted by a metering panel which incorporates the usual jeweled-edge critical flow orifices. Each of the mixture components was metered separately through its own critical flow orifice. The mass spectrometer analyses of these pure gas components are given in Table I. The separate streamswere joined at a mixing tee and passed to the burner.

The cone height of the flame was measured from flame photographs, enlarged on an average to six diameters. The surface area of the flame was then calculated from the equation

$$V_B = \frac{V_G}{\left[1 + 4 \left(\frac{H}{D}\right)^2\right]^{\frac{1}{2}}}$$

Where V_B = Burning velocity in ft./sec.

V_G = Gas velocity in burner in ft./sec.

H = Flame height in centimeters, and

D = Diameter of burner in centimeters

This equation assumes the flame shape to be that of a right circular cone.

Each of the burner inlet gas compositions was calculated to yield a theoretical adiabatic flame temperature of 2250°K at one atmosphere pressure.

The burner inlet gases were fed at a Reynolds number of 1200 except for the stoichiometric mixture. It was found necessary to decrease the flow rate of this mixture to obtain a stable flame.

DISCUSSION

Ten mixtures were calculated for the methane-oxygen-nitrogen system at the 2250°K flame temperatures (Fig. 1 and Tables II and III). The burning velocities of these mixtures were determined on a one-quarter inch tube burner at atmospheric pressure. While these data are incomplete, the results to date are tabulated in Table IV and are shown graphically in Fig. 2. Data for the 2000°K isotherm are also shown for comparison.

It can be seen that at the higher flame temperature (2250°K) the burning velocities were considerably higher. The general shape of the burning velocity isotherm is the same as at the lower (2000°K) flame

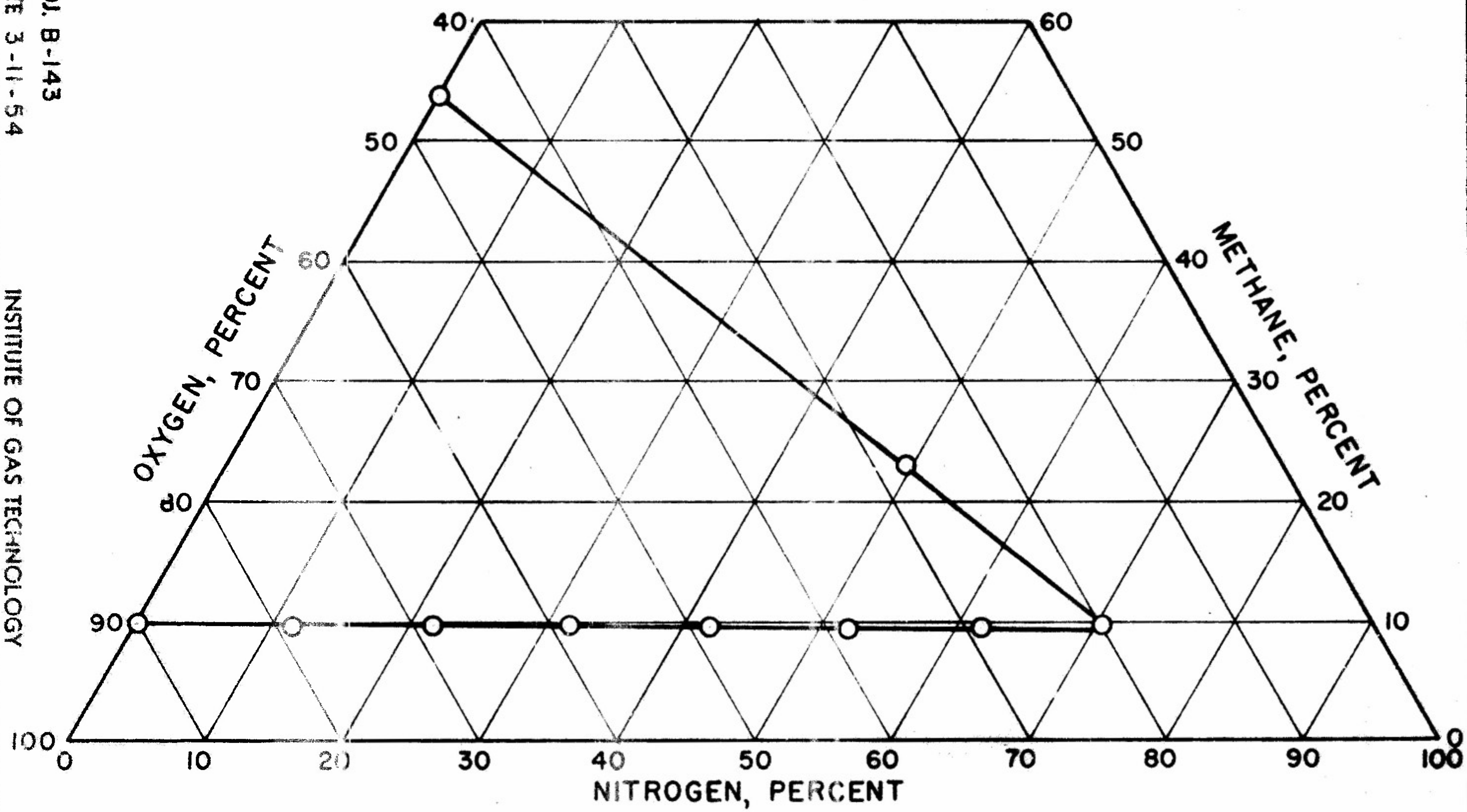

FIG. 1 – COMPOSITION OF THE REACTANT MIXTURES FOR THE CH_4-O_2-N_2 SYSTEM AT 2250° K, ONE ATMOSPHERE PRESSURE

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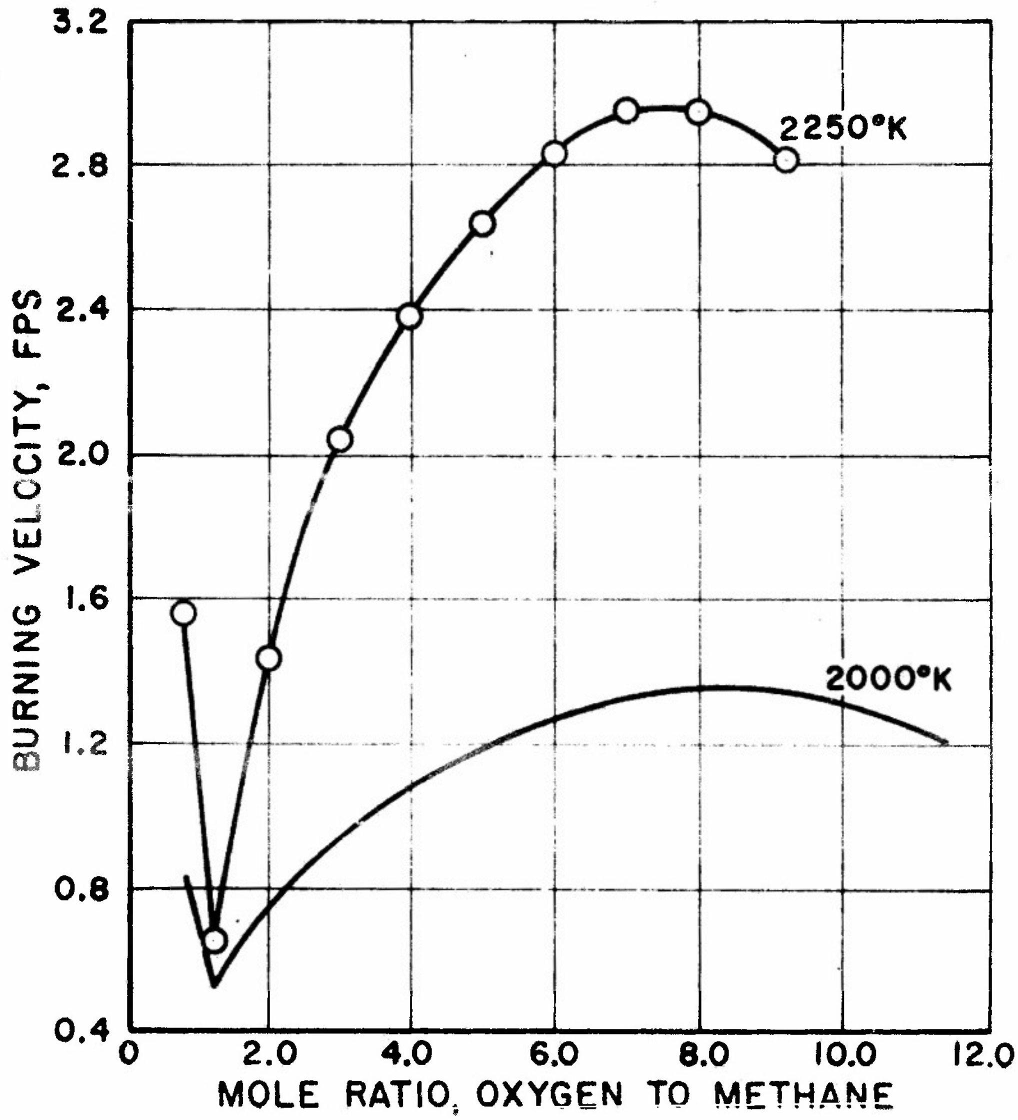

COMPARISON OF BURNING VELOCITIES OF $CH_4-O_2-N_2$ SYSTEMS AT 2250°K AND 2000°K, ONE ATMOSPHERE PRESSURE

temperature. A maximum value was experienced at an oxygen to methane ratio of 8.0:1.0, on the methane-oxygen-nitrogen 2000°K system. The same system at 2250°K was found to exhibit a similar maximum burning velocity in the same fuel-lean range of the isotherm. The stoichiometric mixture resulted in blow-off at a Reynolds number of 1200. The flow rate of this mixture was reduced to a Reynolds number of 825 for the burning velocity determination.

Ten mixtures were calculated for the methane-oxygen-argon and methane-oxygen-helium systems which yield a flame temperature of 2250°K assuming chemical and thermal equilibrium at the flame front and under adiabatic conditions.

The burning velocities of these two systems will be investigated for the purpose of comparison to the same systems at the 2000°K flame temperature. In Report No. 8 the possibility of radial diffusion was presented as being the cause for unexpected results on the methane-oxygen-argon 2000°K system. This investigation, when completed, should establish whether this diffusional mechanism is of importance. The results of these equilibrium calculations on helium and argon mixtures are presented in Tables V and VI.

CONCLUSIONS

(1) Raising the flame temperature from 2000°K to 2250°K displaces the burning velocity of the CH_4-O_2-N_2 system throughout the range of oxygen to methane ratios investigated. The general shapes of both isotherms are similar.

(2) Maximum burning velocities for the CH_4-O_2-N_2 system at both 2000°K and 2250°K were exhibited in the fuel lean range of the isotherms.

RECOMMENDATIONS

(1) Complete the present work on the 2250°K isotherm of the methane-oxygen-nitrogen system and correlate these results.

(2) Complete measurement of the burning velocities for the methane-oxygen-argon and methane-oxygen-helium systems at 2250°K.

(3) Correlate these data and the past (2000°K) data on the same systems with the transport properties of the systems.

TABLE I

Mass Spectrometer Analysis of Gases Used for Determination of the Burning Velocities of the CH_4-O_2-N_2, 2250°K System.

Methane Mole %	Oxygen Mole %	Nitrogen Mole %
99.7 - CH_4	99.7 - O_2	99.75 - N_2
0.1 - C_2H_6	0.2 - CO_2	0.14 - O_2
0.1 - CO_2	0.1 - A	0.01 - CO_2
0.1 - N_2		0.10 - A

TABLE II

Burner Inlet Gas Compositions for the Methane-Oxygen-Nitrogen System at a Theoretical Adiabatic Flame Temperature of 2250°K at One Atmosphere Pressure.

Mole Ratio Oxygen to Methane	Mole Ratio Nitrogen to Methane	Mole Percent Methane	Mole Percent Oxygen	Mole Percent Nitrogen
0.86	0.00	53.87	46.13	0.00
1.2	2.16	22.93	27.52	49.55
2.0	7.28	9.72	19.45	70.83
3.0	6.48	9.54	28.63	61.82
4.0	5.40	9.61	38.46	51.93
5.0	4.31	9.70	48.49	41.82
6.0	3.25	9.76	58.57	31.67
7.0	2.19	9.81	68.67	21.52
8.0	1.16	9.85	78.77	11.38
9.2	0.00	9.81	90.19	0.00

TABLE III

Equilibrium Composition of the Products for the Methane-Oxygen-Nitrogen System at a Theoretical Adiabatic Flame Temperature of 2250°K at One Atmosphere Pressure.

Datum Temperature 300°K

	Oxygen to Methane Ratio				
Products	0.86	1.2	2.0	3.0	4.0
CO_2	0.02524	0.03835	0.08608	0.09244	0.09390
CO	0.30721	0.15449	0.01033	0.00268	0.00191
H_2O	0.21129	0.22498	0.18726	0.18627	0.18726
OH	0.00030	0.00054	0.00284	0.00577	0.00691
H_2	0.45098	0.15896	0.00394	0.00095	0.00067
O_2	0.00000	0.00001	0.00529	0.09086	0.18440
H	0.00498	0.00296	0.00047	0.00023	0.00019
O	0.00000	0.00001	0.00029	0.00121	0.00172
NO	0.00000	0.00610	0.00222	0.00859	0.01118
N_2	0.00000	0.41363	0.70128	0.61188	0.51115
N	0.00000	0.00000	0.00001	0.00000	0.00000

TABLE III (Cont'd)

Equilibrium Composition of the Products for the Methane-Oxygen-Nitrogen System at a Theoretical Adiabatic Flame Temperature of 2250°K at One Atmosphere Pressure

Datum Temperature 300°K

Oxygen to Methane Ratio

Products	5.0	6.0	7.0	8.0	9.2
CO_2	0.09495	0.09587	0.09644	0.09671	0.09654
CO	0.00156	0.00136	0.00121	0.00111	0.00101
H_2O	0.18875	0.18941	0.19006	0.19056	0.19005
OH	0.00770	0.00833	0.00884	0.00927	0.00970
H_2	0.00054	0.00047	0.00042	0.00038	0.00035
O_2	0.28161	0.38019	0.47989	0.57927	0.69915
H	0.00017	0.00016	0.00015	0.00015	0.00014
O	0.00213	0.00247	0.00278	0.00305	0.00335
NO	0.01238	0.01248	0.01151	0.00913	0.00000
N_2	0.41029	0.30903	0.20829	0.10853	0.00000
N	0.00001	0.00001	0.00001	0.00000	0.00000

TABLE IV

Experimental Data for the Methane-Oxygen-Nitrogen System at 2250°K and One Atmosphere Pressure

$\frac{O_2}{CH_4}$	$\frac{H}{D}$ Cone Height / Port Diameter	Q Volumetric Flow Rate at 25°C & 29.92" Hg (CFH)	U Average Gas Velocity at 25°C-29.92"Hg (Ft./Sec.)	N_{Re} Reynolds Number	V_B Burning Velocity (Ft./Sec.)
0.86	6.69	19.197	15.643	1200	1.55
1.2	9.19	10.608	8.644	1200	0.64
2.0	2.65	7.159	5.834	825	1.43
3.0	2.52	10.090	8.222	1200	2.03
4.0	2.15	9.921	8.084	1200	2.38
5.0	1.93	9.916	8.080	1200	2.64
6.0	1.81	10.079	8.213	1200	2.83
7.0	1.79	10.403	8.477	1200	2.95
8.0	1.95	10.881	8.867	1200	2.94
9.2	2.14	11.602	9.454	1200	2.81

TABLE V

Burner Inlet Gas Compositions for the Methane-Oxygen-Argon and Methane-Oxygen-Helium Systems at a Constant Theoretical Adiabatic Flame Temperature of 2250°K at One Atmosphere Pressure

Mole Ratio Oxygen to Methane	Mole Ratio Inert to Methane	Mole Percent Methane	Mole Percent Oxygen	Mole Percent Argon or Helium
0.86	0.00	53.87	46.13	0.00
1.2	3.77	16.75	20.10	63.15
1.6	8.16	9.29	14.87	75.84
2.0	11.45	6.92	13.84	79.24
3.0	10.59	6.85	20.57	72.58
4.0	7.15	8.23	32.94	58.83
5.0	7.14	7.61	38.04	54.36
6.0	5.46	8.02	48.14	43.83
7.0	3.75	8.51	59.58	31.91
8.0	2.06	9.04	72.34	18.62
9.2	0.00	9.81	90.19	0.00

TABLE VI

Equilibrium Composition of the Products for the Methane-Oxygen-Argon and Methane-Oxygen-Helium Systems at a Theoretical Adiabatic Flame Temperature of 2250°K at One Atmosphere Pressure

Datum Temperature 300°K

OXYGEN TO METHANE RATIO

Products	0.86	1.2	1.6	2.0	3.0	4.0
CO_2	0.02524	0.03074	0.04447	0.05869	0.06616	0.07025
CO	0.30721	0.11666	0.04504	0.01025	0.00222	0.00162
H_2O	0.21129	0.17609	0.15113	0.13259	0.13359	0.14029
OH	0.00030	0.00049	0.00088	0.00198	0.00454	0.00561
H_2	0.45098	0.11719	0.02684	0.00406	0.00078	0.00057
O_2	0.00000	0.00000	0.00007	0.00250	0.06795	0.14271
O	0.00000	0.00001	0.00003	0.00020	0.00104	0.00151
H	0.00498	0.00254	0.00121	0.00047	0.00021	0.00018
A or He	0.00000	0.55629	0.73032	0.78925	0.72351	0.63726

TABLE VI (Cont'd)

Equilibrium Composition of the Products for the Methane-Oxygen-Argon and Methane-Oxygen-Helium Systems at a Theoretical Adiabatic Flame Temperature of 2250°K at One Atmosphere Pressure

Datum Temperature 300°K

OXYGEN TO METHANE RATIO

Products	5.0	6.0	7.0	8.0	9.2
CO_2	0.07442	0.07876	0.08367	0.08904	0.09665
CO	0.00137	0.00122	0.00113	0.00106	0.00101
H_2O	0.14779	0.15586	0.16513	0.17539	0.19005
OH	0.00645	0.00722	0.00797	0.00873	0.00971
H_2	0.00048	0.00042	0.00039	0.00037	0.00035
O_2	0.22587	0.31732	0.42114	0.53693	0.69915
O	0.00190	0.00226	0.00260	0.00294	0.00335
H	0.00016	0.00015	0.00015	0.00014	0.00014
A or He	0.54155	0.43679	0.31783	0.18541	0.00000